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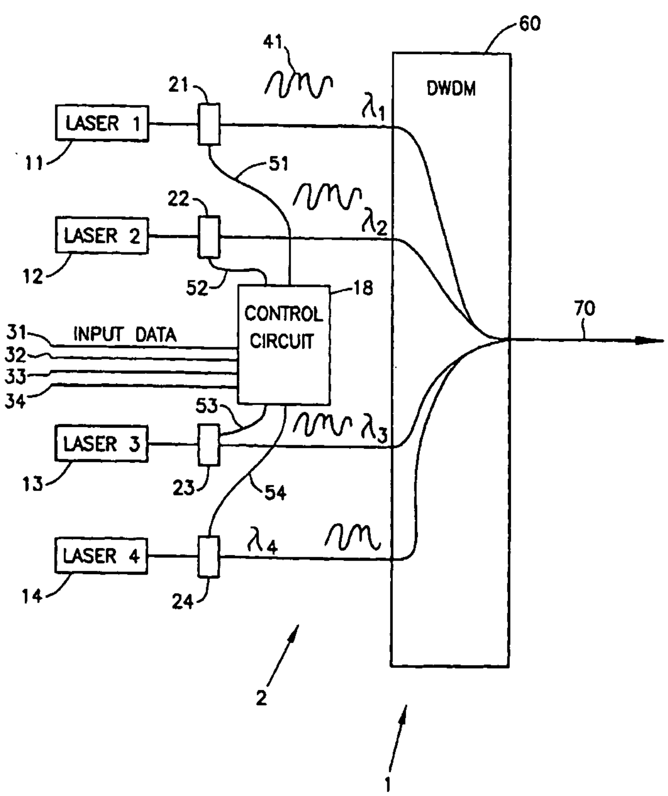
(54) Title: SECURE WAVE-DIVISION MULTIPLEXING TELECOMMUNICATIONS SYSTEM AND METHOD



(57) Abstract: A fiber optic data transmission system includes an optical fiber and a data transmitter having a first laser (11) having a first wavelength, a first phase modulator (21) for phase modulating light from the first laser as a function of a first data input stream (31) so as to create a first phase-modulated output data stream, a second laser (12) having a second wavelength different from the first wavelength, and a second phase modulator (22) for phase modulating light from the second laser as a function of a second data input stream (32) so as to create a second phase-modulated output data stream. The transmitter also includes a combiner (60) combining the first and second output data streams into a phase-modulated optical signal for transmission over the optical fiber (70).

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SECURE WAVE-DIVISION MULTIPLEXING TELECOMMUNICATIONS SYSTEM AND METHOD

BACKGROUND OF THE INVENTION

The present invention relates generally to telecommunications and more particularly to improving security and data transmission over wave-division multiplexed fiber optic networks.

In current fiber optic networks, an electronic data stream is fed to a laser amplitude modulator. The laser amplitude modulator typically pulses or alters the laser output to create an amplitude-modulated optical signal representative of the electronic data stream. The laser amplitude modulator and laser thus define a transmitter for transmitting the optical signal over an optical fiber, which is then received by a receiver. The receiver for the amplitude-modulated optical signals of the optical data typically includes a photodiode to convert the optical signals back into the electronic data stream.

The reading of the amplitude-modulated optical data signals using a photodiode is straightforward: the optical signals either produce an electric output at the photodiode or they do not. As a result, an output electronic data stream of zeros and ones is generated.

However, optical fiber may be tapped. The optical fibers can be spliced or even merely clamped so as to obtain optical signals from the fiber. It also may be possible to tap fibers without physically touching the optical fiber, for example by reading energy emanating or dissipating along the fiber. Amplitude-modulated optical signals, with their ease of detection from a photodiode, require that only a small amount of energy be tapped and passed through the photodiode in order to be

converted into a tapped electronic data stream.

To confront non-secure optical and non-optical data lines, it has been known to use public key/private key encryption so that the data stream being transmitted is encoded in a format that makes it difficult to decode. Encryption however has several drawbacks, including the need for extra processing steps and time. Moreover, public key/private key encrypted data can be cracked, and the devices and algorithms for doing so are constantly improving.

U.S. Patent No. 5,455,698 purports to disclose a secure fiber optic communications system based on the principles of a Sagnac interferometer. A data transmitter is a phase modulator for modulating counter-propagating light beams sent by a receiver round a loop. The receiver includes a light source, a beamsplitter for splitting light from the light source into counter-propagating light beams and for receiving the phase-modulated light beams, and an output detector. U.S. Patent No. 5,223,967 describes a similar Sagnac-interferometer-based system operating over a single optical fiber.

The Sagnac-interferometer-based systems described in these patents have the disadvantage that they require the light to travel over a loop, whether back and forth in a single fiber or over a long length looped fiber. As a result, either the link budget for the single fiber must be doubled, reducing the data carrying capacity for a single fiber, or else a looped fiber with significant and expensive extra length of at least twice that of a single fiber must be laid between the transmitter and the receiver. Moreover, the receiver contains the light source, as opposed to the current installed base where the transmitter has the light source.

The Sagnac-interferometer-based systems thus are expensive to build and operate, and do not work particularly well with existing systems. Moreover, because a broadband light source is desired for Sagnac-intereferometer based systems (see 5,455,698 patent at col 1, lines 66 et seq.), these systems do not work well with wavelength division multiplexed (WDM) systems in which data is transmitted over different wavelengths.

The 5,455,698 patent describes splitting a wavelength division multiplexed system with three different wavelengths. However, two of the waevelengths are guard bands strictly used for alarm dteection and not for information transmitting. See, e.g., the '698 patent at col. 13, lines 44-55.

U.S. Patent No. 6,072,615 purports to describe a method for generating a return-to-zero optical pulses using a phase modulator and optical filter. The RZ-pulse optical signal transmitted over the fiber is easily readable by a detector.

U.S. Patent No. 5,606,446 purports to describe an optical telecommunications system employing multiple phase-compensated optical signals. Multiple interferometric systems are combined for the purpose of multiplexing various payloads on the same optical transmission path. The patent attempts to describe a method for providing fiber usage diversity using optical coherence length properties and a complex transmit/receive system. Each transmitter has a splitter, a plurality of fibers and a plurality of phase modulators to create the multiplexed signal, which is then demultiplexed at the receiver. This system is complex and expensive.

U.S. Patent No. 5,726,784 purports to describe a WDM optical communications system with remodulators and diverse optical transmitters. An external modulator is used to impart an amplitude-modulated output signal for each wavelength, as described in colum 6, lines 14 to 36 of the '784 patent. Optoelectronic detectors can easily read these amplitude-modulated signals. The entirety of U.S. Patent No. 5,726,784 is hereby incorporated-by-reference herein.

SUMMARY OF THE INVENTION

An object of the present invention is to provide an improved security WDM transmission system and device. Yet another alternate or additional object of the present invention is to provide a simple yet secure phase-modulated optical data transmission system usable in a WDM system.

The present invention provides a fiber optic data transmission system comprising a transmitter having a first laser having a first wavelength, a first phase modulator for phase modulating light from the first laser as a function of a first data input stream so as to create a first phase-modulated output data stream, a second laser having a second wavelength different from the first wavelength, and a second phase modulator for phase modulating light from the second laser as a function of a second data input stream so as to create a second phase-modulated output data stream. A combiner combines the first and second output data streams into a phase-modulated optical signal, which is transmitted over an optical fiber.

Preferably, a controller controls the first phase modulator as a function of an output of a delayed-feedback exclusive-or gate having the first input data stream as an input. The controller also preferably controls the second phase modulator as a function of an output of another delayed-feedback exclusive-or gate.

The present system also includes a receiver receiving the optical signal from the optical fiber. The receiver includes a WDM/DWDM splitter for splitting the optical signal into a first path with the first wavelength and a second path with the second wavelength. A first delayed-arm interferometer receives the first path and a second delayed-arm intereferometer receives the second path.

The first laser preferably is a continuous wave laser, for example a semiconductor laser operating at 1550.92 nm, with the second laser being for example a continuous wave semiconductor laser operating at 1546.12 nm. However, other wavelengths are possible.

The receiver may include detectors for converting the output optical signals from the interferometers into electronic output data streams. Filters may be provided to reduce any noise at the output signal.

The system preferably includes a detector for detecting a tap or loss of energy in the optical fiber. Most preferably, the detector is an energy sensor, which may or may not

include programmable "trip" levels, which can monitor the amplitude of the light in the fiber. If a tap occurs, it must couple off a significant amount of energy to pass through an interferometer with a low bit error rate, thus making detection of the tap by the detector highly likely. The energy detector preferably is located upstream from the WDM/DWDM splitter.

Depolarizers preferably are located between the lasers and the respective phase modulators, and in one arm of the interferometers of the receiver.

The present invention also provides a transmitter comprising a first laser having a first wavelength, a first phase modulator for phase modulating light from the first laser so as to form a phase-modulated first optical data stream, a second laser having a second wavelength different from the first wavelength, a second phase modulator for phase modulating light from the second laser so as to form a phase-modulated second optical data stream, a combiner for combining the phase-modulated first and second optical data streams, and a controller controlling the first and second phase modulators as function of a first input electronic data stream and a second input electronic data stream. The controller preferably includes a first delayed-feedback exclusive-or gate and a second delayed-feedback exclusive-or gate.

In addition, the present invention also provides a receiver comprising an optical splitter for splitting light into a first wavelength and a second wavelength different from the first wavelength, and a first interferometer receiving light at the first wavelength and a second interferometer receiving light at the second wavelength.

The optical WDM/DWDM splitter preferably includes a Bragg grating.

A method for transmitting secure data is also provided comprising the steps of: transmitting light from a first laser at a data transmitter; phase modulating light from the first laser at the data transmitter as a function of a first electronic data input stream; transmitting light from a second laser having a wavelength different from the first laser; phase modulating light from the second laser at the data transmitter as a

function of a second electronic data input stream; and combining light from the first and second lasers so as to create a combined output signal with phase-modulated data.

Preferably, the phase modulated data is a function of outputs of delayed-feedback exclusive-or gates. Preferably, all of the light from the first and second lasers is phase-modulated.

The method further may include receiving the phase-modulated combined optical signal in a receiver, and splitting the combined output signal into a first and second path as a function of wavelength. The first and second paths are then each passed through an interferometer.

The method preferably includes monitoring a fiber for intrusion. The monitoring preferably includes monitoring an energy level in the fiber with programmable trip levels.

While the invention has been described with two different wavelength lasers, more lasers are of course possible.

BRIEF DESCRIPTION OF THE DRAWINGS

A preferred embodiment of the present invention is described below by reference to the following drawings, in which:

Fig. 1 shows a transmitter of the present invention;

Fig. 2 shows a receiver of the present invention; and

Fig. 3 shows details of the control system of Fig. 1.

Fig. 4 shows details of an electronic data stream and the respective phase-modulated optical signals for the first wavelength channel, in representative binary form;

Fig. 5 shows details of another electronic data stream and phase-modulated optical signals resulting for the first wavelength channel of the present invention, in representative binary form;

Fig. 6 shows details of the embodiment of an alternate controller with a phase-compensating circuit to replace the gate 131 in Fig. 3, with similar controllers each for replacing gates 132, 133 and 134;

Fig. 7 shows details of a simplified example of the functioning of the controller in Fig. 6;

Fig, 8 shows results of a desired initial synchronization result for the controller in Fig. 6;

Fig. 9 shows details of an alternate embodiment of the interferometers of Fig. 2; and

Fig. 10 shows schematically the exclusive-or optical function of an interferometer with a 180-degree phase shift.

DETAILED DESCRIPTION

Fig. 1 shows a preferred embodiment of a secure telecommunications system 1 with wave division multiplexing according to the present invention. The system 1 includes a transmitter 2 with continuous wave coherent lasers 11, 12, 13 and 14, each for example a semiconductor laser emitting a narrow band of light at 1557 nm, 1554 nm, 1551 nm and 1548 nm, respectively. Other wavelengths however are possible. Light emitted from lasers 11, 12, 13, 14 is depolarized and then passes through phase modulators 21, 22, 23, 24, respectively, each for example a Mach-Zender phase modulator. An electronic controller 18 controls phase modulators 21, 22, 23, 24 as a function of four input electronic data streams 31, 32, 33, 34, respectively. Controller 18 is also programmable to control the optical power output of light emitted by lasers 11, 12, 13, 14. Preferably, the power output of the lasers is set as low as possible for a given optical span, while maintaining a low bit error rate. This reduces the light

available for any tap.

Depending on the binary output 51 of controller 18, phase modulator 21 either imparts a first phase shift to the light (for example, zero) or a second phase shift different from the first phase shift (for example, 180 degrees) on the light passing through phase modulator 21, thus creating a phase-modulated optical signal 41, which represents a stream of binary bits. The first phase shift for example represents a binary zero and the second phase shift a binary one. Likewise, phase modulators 22, 23, 24, as a function of outputs 52, 53, 54 of controller 18 respectively, impart a first phase shift or second phase shift on light from lasers 12, 13, 14, respectively. Thus independent data streams 41, 42, 43, 44 are created.

Fig. 3 shows a respresentation of the control circuit of controller 18. Each input electronic data stream 31, 32, 33, 34 is fed through a delayed-feedback exclusive-or gate 131, 132, 133, 134, respectively. Each feedback delay of each gate 131, 132, 133, 134 may equal, for example, a number of bits. The feedback delays may be the same or, preferably, differ among the gates 131, 132, 133, 134. The binary output streams 51, 52, 53, 54 are used to phase modulate the light from lasers 11, 12, 13, 14, respectively, to create the phase-modulated optical data streams 41, 42, 43, 44.

Optical data streams 41, 42, 43, 44 are combined in a combiner 60 which combines the light at the different wavelengths and sends it over a fiber 70.

Light from fiber 70 is received in a receiver 3 according to the present invention. A splitter 80 splits off a portion of the light, directing part of the optical energy to the light monitoring detector 82 and passing the remaining light to a wave division splitter 90 preferably having a Bragg grating 91.

A detector 82, for example a light energy detector, monitors the light energy in the fiber 70 via the light energy coupled to the detector by splitter 80, the light energy being a function of the amplitude. If the amplitude drops, most likely from a tap, the detector alerts the receiver and can, for example, sound an alarm or alert network

maintenance personnel. Additionally, since the receiver 3 is generally part of a component box, which also includes a transmitter, the component box transmitter can send a signal back to the component box containing transmitter 2 so as to instruct transmitter 2 to stop sending data, or to send data over a standby fiber. Detector 82, while preferably part of receiver 3, also could be located separately from receiver 3, for example where fiber 70 enters a building or other secure environment.

WDM splitter 90 splits the light into the four wavelengths originally sent by lasers 11, 12, 13 and 14 to paths 71, 72, 73, 74. Each path 71, 72, 73, 74 enters a delayed-arm interferometer 92, 93, 94, 95. The delay loop of each interferometer 92, 93, 94, 95 corresponds to the electronic feedback delay in each of the circuits 131, 132, 133, 133, respectively.

The phase-modulated data as it passes through the respective interferometer 92, 93, 94, 95 either constructively interferes or destructively interferes, since the second arm of the interferometer can be contructed to provide a 180 degree phase shift, so as to create signals read by detectors 101, 102, 103, 104, the signals being representative of input data 31, 32, 33, 34, respectively.

Filters 111, 112, 113 and 114 are provided to compensate for any slight mismatch between the optical delay in the interfermometer and the electronic delay, and for other noise.

Fig. 4 shows a schematic example of the functioning of one wavelength channel with a two-bit delay imposed by the feedback loop in circuit 131 of Fig. 2 and using either the 180-degree phase-shift receivers shown in Fig. 2 or in Fig 9. The electronic data stream input DSI is also the input B for exclusive-or gate 118. The first two delayed bits from input A are determined by the previous two bits in stream B, and as will be demonstrated with respect to Fig. 5, do not affect the functioning of the wavelength channel. Assuming for purposes of Fig. 4 that the delayed bits 64 entered input A as zero and zero, the output OP is as shown. Phase modulator 21 then converts this electronic data stream OP into optical signal 41 representative of OP. The

interferometer 92, using a delay arm, then creates delayed optical signal OPD, also delayed two bits from the optical signal representative of OP. At combiner 36, the two signals OP and OPD produce, at output 42 and photodiode detector 101, the data stream output DSO. As shown schematically in Fig. 10, line 401 for example represents the waveform for a binary zero in first arm (and a one in second arm) and line 402 represents the waveform for a binary one in the first arm (and a zero in the second arm) at coupler 42. Thus two binary zeros or two binary ones will interfere to produce a zero voltage at photodetector 38, while a binary zero and binary one combination will produce an output voltage, which is interpreted as a one. As shown, input data stream DSI and output data stream DSO are the same.

Fig. 5 shows the effect of having a different first two delayed bits 65 from input A on the same data stream input DSI of Fig. 4. While the data stream OP and OPD thus differ from those in Fig. 4, the resulting data stream output DSO is the same as in Fig. 4.

The 180 phase-difference interferometers provide a secure method for transmitting data over a single optical fiber, which is difficult to decode if tapped, and also permits excellent detection of the existence of a tap.

While the circuit 131 is for use with a 180 degree phase-shift interferometer 92. Alternatively, the embodiment provided in Fig. 6 with the phase-compensation circuit 210 may be used for one wavelength channel with an interferometer of any phase-difference, and is preferred if additional security is desired. Each transmitter with controller circuit 218 thus may be synchronized or "married" to an interferometer having a unique phase difference PD between the two arms.

Circuit 218 includes an N-bit register 230 that receives a phase-compensation signal determined during a synchronization routine to set N-bit register 230. The N-bit register 230 sets a phase-compensation to be combined with a digital signal input DSI. The N-bit register 230 value is input to input B1 of an arithmetic logic unit 232, which adds input A1, A1 being a feedback loop, to input B1 in a summing operation

without carry. The summing operation is clocked at the maximum of: (1) the rate of the digital signal input, DS1, or (2) the digital input signal rate divided by the number of bits of delay, Z, in circuit 238, i.e. if the number Z is less than one, the summing operation operates at a rate faster than the digital signal input rate. ALU 232 thus continually adds the value of register 230 for each operation. The combined output A3 of ALU 232 is fed to a digital-to-analog converter 234, with the most significant bit of the ALU output A3 first passing through an exclusive-or gate 236 and the other N-1 bits being fed directly to D-A converter 234. Thus input A4 has a first bit which is the exclusive-or gate 236 output, and the remaining bits being the N-1 least significant bits remaining from A3.

D-A converter 234 provides a voltage output corresponding to the digital input A4, which then controls the phase modulator 16. The phase modulator 16 shifts the optical signal by an amount proportional to the voltage applied over a full 360-degree range. The D-A converter 234 thus can control the phase modulator 16 to a resolution of (360 degrees/ 2^N), with a zero input corresponding to zero volts and zero phase shift, and each additional binary one added to the digital input A4 increasing the voltage output by converter 234 so that the phase modulator 16 produces an additional phase of (360 degrees/ 2^N).

Exclusive-or gate 236 receives its other input A2 from digital signal input DSI being passed through a delayed-feedback exclusive-or gate 238, which has a Z-bit delay.

Referencing Fig. 2, if Q2 represents the phase imparted from the input of the interferometer 92 through the second, delayed path of the interferometer 92 to the coupler output 42 and Q1 the phase imparted in the first path to the coupler output 42, then the phase compensation desired to be provided by the phase-compensation circuit 210 per bit in degrees is [(Q2-Q1-180)/max(Z,1)] mod 360. Since the phase-compensation resolution increases very quickly by the factor N, a very precise control of the phase modulator 21 can be achieved.

The transmitter circuit with compensation circuit 210 thus provides that the phase for

each bit is rotated slightly, so that when the signals are passed through interferometer 92, a binary zero results in zero voltage and a binary one in a detectable voltage at photodetector 101.

A simplified example of the phase-compensation circuit 210 and control circuit 218 is shown with reference to Fig. 7 using a three-bit register with a one-bit delay in the gate 238. Typically N would be much larger than 3, for example 64, and most preferably at least 32.

Assume for example that the first arm of interferometer 92 in Fig. 2 imparts a 15 degree phase shift from the input to output 42, and that the second arm including fiber 45 imparts a phase shift of 240 degrees from the input to output 42 and provides a one-bit delay. The resulting desired phase compensation is (240-15)-180=45 degrees to be imparted on the each bit of stream A2. Since the D-A converter 234 is a 3-bit converter, a digital three- bit binary word of input A4 of 001 provides a voltage to the phase modulator 16 that results in a phase shift of 45 degrees, 010 provides a phase shift of 90 degrees, 011 of 135 degrees, 100 of 180 degrees, 101 of 225, 110 of 270, 111 of 315 and 000 of zero degrees.

The desired phase compensation is determined during a synchronization routine where a known data stream is transmitted as input DSI to gate 238 and sent to the receiver and through an interferometer with phase difference PD equal to 240-15=225. The N-bit register 230 is altered until the data stream results at detector 38, which in this case results when the N-bit register has the value 001, which corresponds to PD-180 degrees, or 45 degrees. Once the synchronization is complete, the desired N-bit value 001 is set. Fig 8 provides an example of how a known data stream of zeros, for this example, result from the N-bit value 001. A2 is a string of zeros. A3 is the sum of the N-bit register output, i.e. 000 001 010 011, so that a binary 001 is added for every output. The first bit (most significant bit) is combined with A2, which results in no change. Thus A4 equals A3 as shown, which is a continual adding of the N-bit register 230 output 001. The phase in the fiber is thus continually rotated 45 degrees for each bit. The first arm signal gains 15 degrees from

input 41 to output 42, and the second arm is signal is delayed one bit and gains 240 degrees to output 42. The signals in the two arms then always combining to interfere at 180 degrees (or 540 degrees) from each other to provide no voltage at photodetector 38, resulting in zeros being output.

Returning to Fig. 7, a data input stream DSI may now be supplied, with register 230 set at 001 as determined by the synchronization period. Assuming the first bit sent back from the feedback loop of gate 238 in Fig. 6 is zero, the output A2 of the exclusive-or gate 238 is as shown. The gate 236 results in the MSB of A3 being altered by the bits from A2, so that A4 as shown results. The D-A converter 234 then controls the phase modulator 21 so that the phase in the fiber for each bit is as shown. The signals gain 15 degrees in the first fiber arm, and are delayed one bit and gain 240 degrees in the second fiber arm. If the phases are the same or 360 degrees apart, a voltage is registered at the photodetector 101, and if the phases are 180 degrees apart, the signals interfere and a zero is registered, as shown by the output. DSI and the output correspond.

The N-bit register however in practice will be much larger than 3 bits to provide a much higher phase-compensation resolution.

Even with a high-bit compensation circuit, for example 64 bits, the actual phase difference imparted in the transmitter will vary slightly over time from that of the interferometer due to quantization error. The output modulation depth will thus begin to slightly degrade, as the phases depart from perfect interference at 180 degrees. A correction circuit at the receiver is then provided to determine modulation depth degradation. At a certain threshold voltage, the receiver can send back, via a transmitter (the receiver and another transmitter typically are paired in a transceiver card) for example in user-defined bits of a packet, a correction signal to the transmitter. The correction signal alters the N-bit register by one or more bits at the least significant bit in a first direction (adds or subtracts a correction value). If a correction results at the receiver so that the modulation depth degradation is lessened, the N-bit register 230 is set at the new altered value. If the modulation depth

degradation increases as a result of the correction, the correction value is doubled and applied to the N-bit register in the other direction (subtracts or adds, whichever is opposite of the initial correction). The voltage produced by zeros at output 42 will then approach zero again.

The coherence length of the laser 11 should be greater than the longer of the delay arms in the interferometer 92.

To create a 180-degree phase shift in interferometer 92, it is possible to place a phase modulator 310 in one arm of the interferometer 300, as shown in Fig. 9.

If a receiver phase modulator 310 is placed in one path of the interferometer 300 as in Fig. 9, then the phase may be altered so that a 180-degree phase difference results between the two paths. The exact voltage to be supplied to the phase-modulator 310, and thus the phase imparted, may determined during manufacturing by placing a CW stream at the input of the interferometer and altering the voltage to the phase modulator until zero voltage results at photodetector 101.

WHAT IS CLAIMED IS:

1. A fiber optic data transmission system comprising:

an optical fiber; and

a data transmitter having a first laser having a first wavelength, a first phase modulator for phase modulating light from the first laser as a function of a first data input stream so as to create a first phase-modulated output data stream, a second laser having a second wavelength different from the first wavelength, and a second phase modulator for phase modulating light from the second laser as a function of a second data input stream so as to create a second phase-modulated output data stream, the transmitter further including a combiner combining the first and second output data streams into a phase-modulated optical signal for transmission over the optical fiber.

2. The system as recited in claim 1 further comprising a controller controlling the first phase modulator as a function of an output of a delayed-feedback exclusive-or gate having the first input data stream as an input.

3. The system as recited in claim 2 wherein the controller controls the second phase modulator as a function of another output of another delayed-feedback exclusive-or gate.

4. The system as recited in claim 1 further comprising a receiver receiving the phase-modulated optical signal from the optical fiber, the receiver including a splitter for splitting the optical signal into a first path with the first wavelength and a second path with the second wavelength.

5. The system as recited in claim 4 wherein the receiver includes a first interferometer receiving the first path and a second intereferometer receiving the second path.

6. The system as recited in claim 1 further comprising a detector for detecting a tap or loss of energy in the optical fiber.

7. A transmitter comprising:

a first laser having a first wavelength;

a first phase modulator for phase modulating light from the first laser so as to form a phase-modulated first optical data stream;

a second laser having a second wavelength different from the first wavelength,

a second phase modulator for phase modulating light from the second laser so as to form a phase-modulated second optical data stream,

a combiner for combining the phase-modulated first and second optical data streams, and

a controller controlling the first and second phase modulators as function of a first input electronic data stream and a second input electronic data stream.

8. The transmitter as recited in claim 7 wherein the controller includes a first delayed-feedback exclusive-or gate and a second delayed-feedback exclusive-or gate.

9. The transmitter as recited in claim 7 further comprising a plurality of further lasers having different wavelengths.

10. A receiver comprising:

an optical splitter for splitting light into a first wavelength and a second wavelength different from the first wavelength, and a first interferometer receiving light at the first wavelength and a second interferometer receiving light at the second wavelength.

11. The receiver as recited in claim 10 wherein the optical splitter includes a Bragg grating.

12. The receiver as recited in claim 10 further comprising a detector for detecting a tap or loss of energy in the optical fiber.

13. The receiver as recited in claim 10 further comprising a plurality of further interferometers.

14. A method for transmitting secure data is also provided comprising the steps of:

transmitting light from a first laser at a data transmitter;

phase modulating light from the first laser at the data transmitter as a function of a first electronic data input stream so as to create a first output data stream, a first binary bit being represented by a first phase and a second binary bit being presentated by a second phase different from the first phase;

transmitting light from a second laser having a wavelength different from the first laser;

phase modulating light from the second laser at the data transmitter as a function of a second electronic data input stream so as to create a second output data stream; and

combining the first and second output data streams.

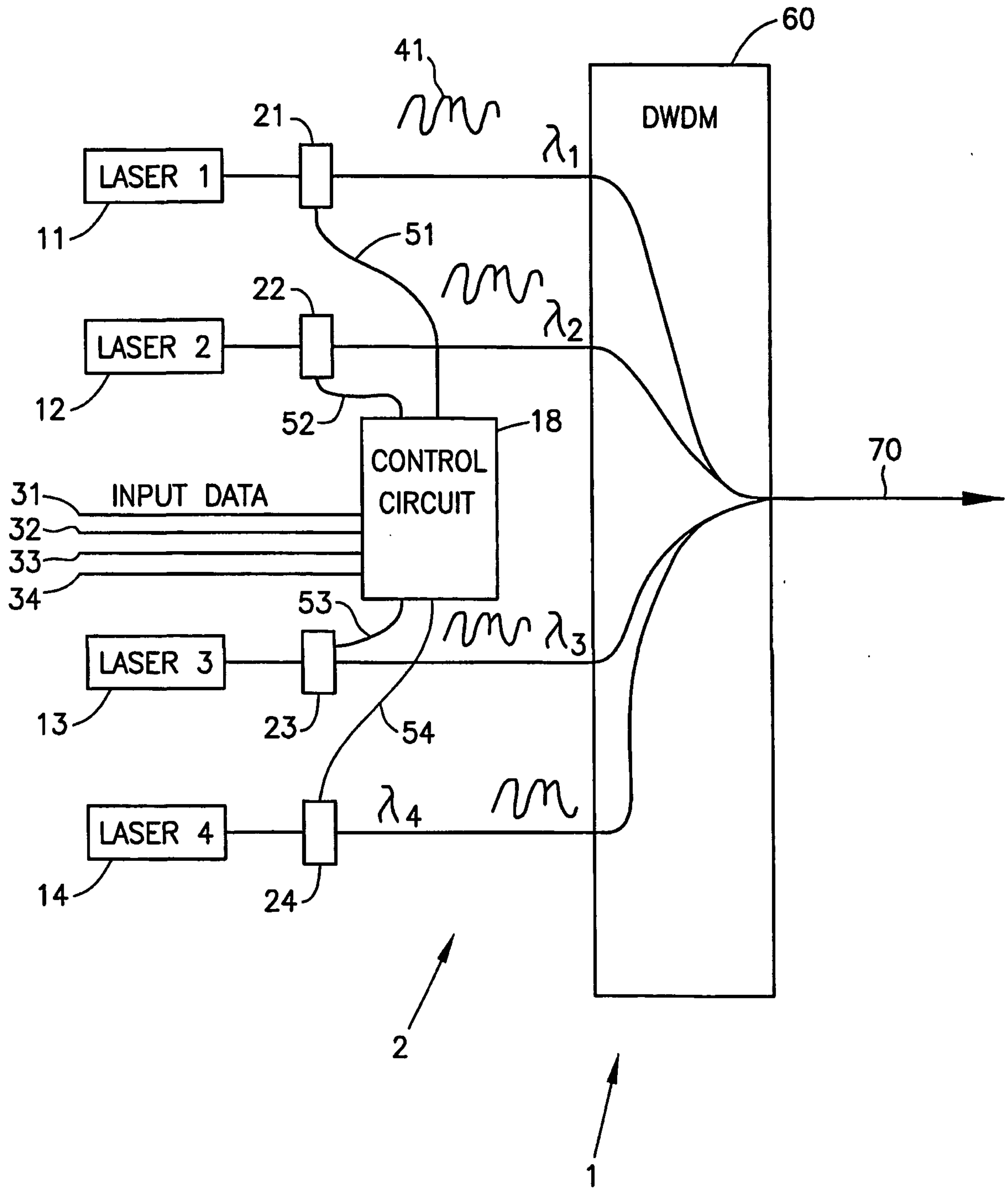
15. The method as recited in claim 14 wherein the phase modulated data is a function of outputs of delayed-feedback exclusive-or gates.

16. The method as recited in claim 14 wherein all of the light from the first and second lasers is phase-modulated.

17. The method as recited in claim 14 further including receiving the phase-modulated combined optical signal in a receiver, and splitting the combined output signal into a first and second path as a function of wavelength.

18. The method as recited in claim 17 further comprising passing each of the first and second paths through an interferometer.

19. The method as recited in claim 14 further including monitoring a fiber for intrusion.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LASER 1
11
51
22
λ_2
LASER 2
12
52
18
CONTROL CIRCUIT
70
31
INPUT DATA
32
33
34
53
λ_3
LASER 3
13
23
54
λ_4
LASER 4
14
24
2
1

Fig. 1

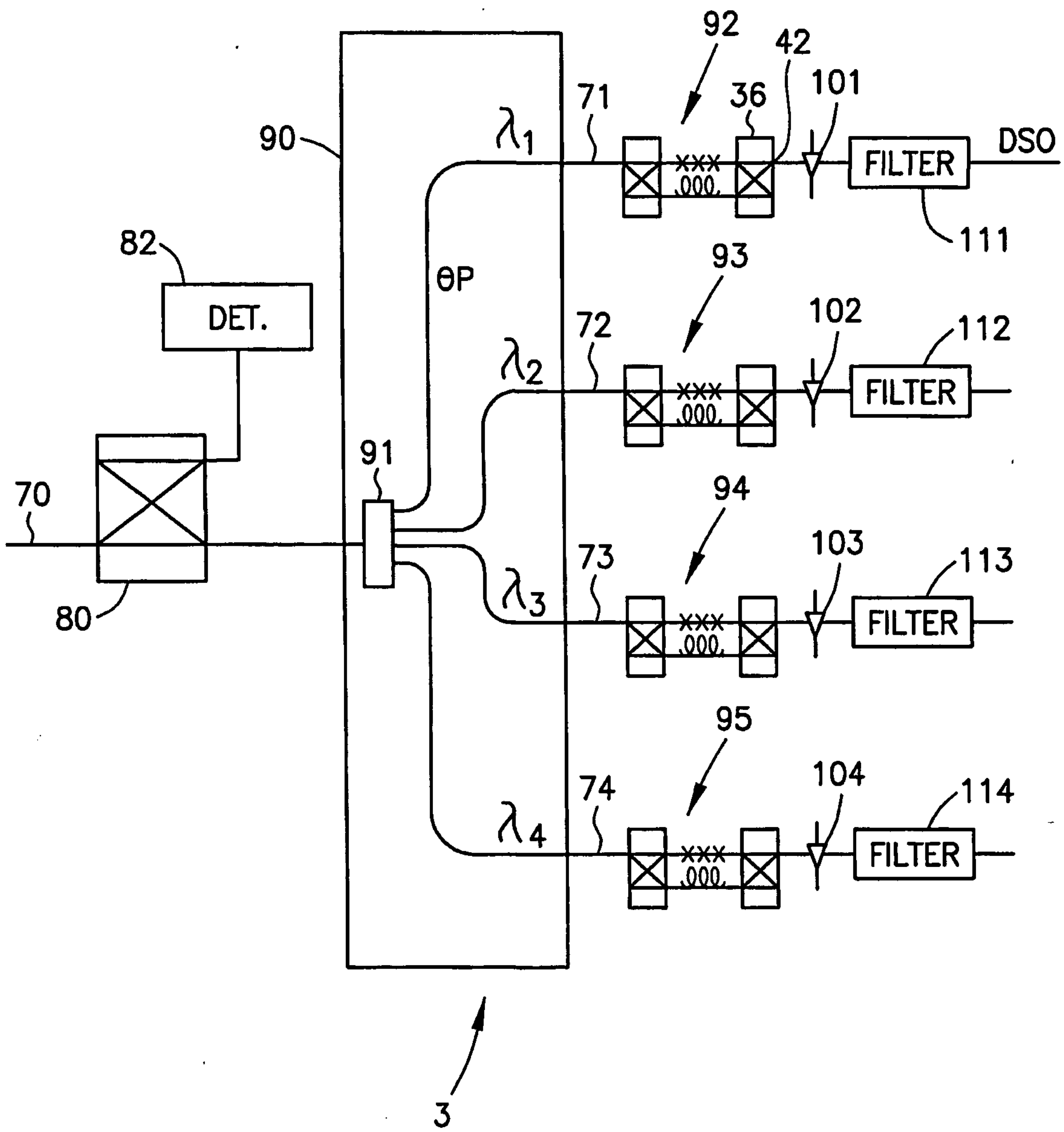
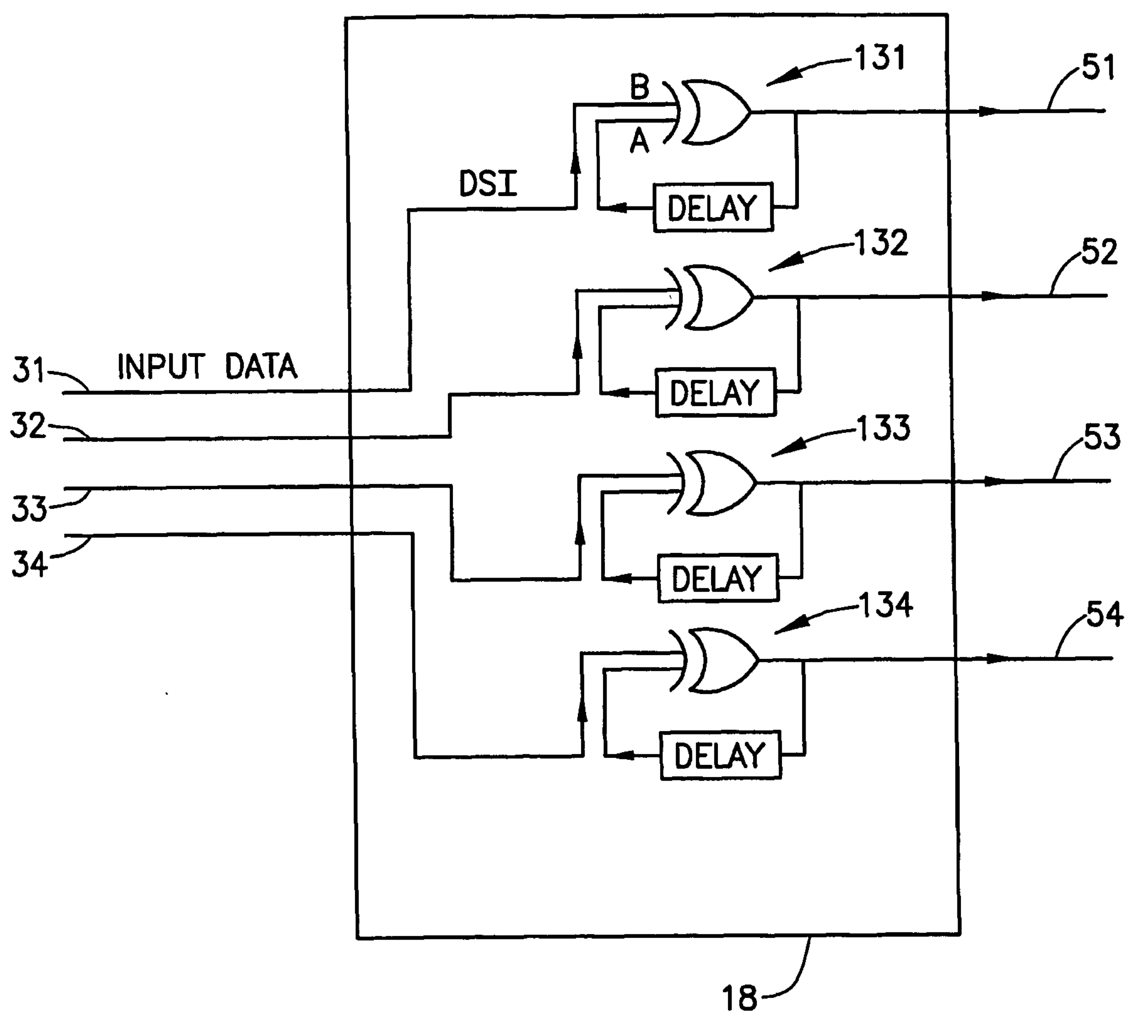

92
42
71
36
101
90
λ_1
DSO
FILTER
82
111
θP
93
DET.
102
72
112
λ_2
FILTER
91
94
70
103
73
113
λ_3
FILTER
80
95
104
74
114
λ_4
FILTER
3

Fig. 2



131
132
133
134
51
52
53
54
B
A
DSI
DELAY
DELAY
DELAY
DELAY
31
32
33
34
INPUT DATA
18

Fig. 3

```
                                ← time
DSI  0101001110110101111101101011101

A    0100001101101110011011011100100 ← 64
B    0101001110110101111101101011101

OP   0001000011011011100110110111001
OPD  01000011011011100110110111001__

DSO  01010011101101011111011010111__
```

Fig. 4

```
                                ← time
DSI  0101001110110101111101101011101

A    0001011000111011001110001001110 ← 65
B    0101001110110101111101101011101

OP   0100010110001110110011100010011
OPD  00010110001110110011100010011__

DSO  01010011101101011111011010111__
```

Fig. 5

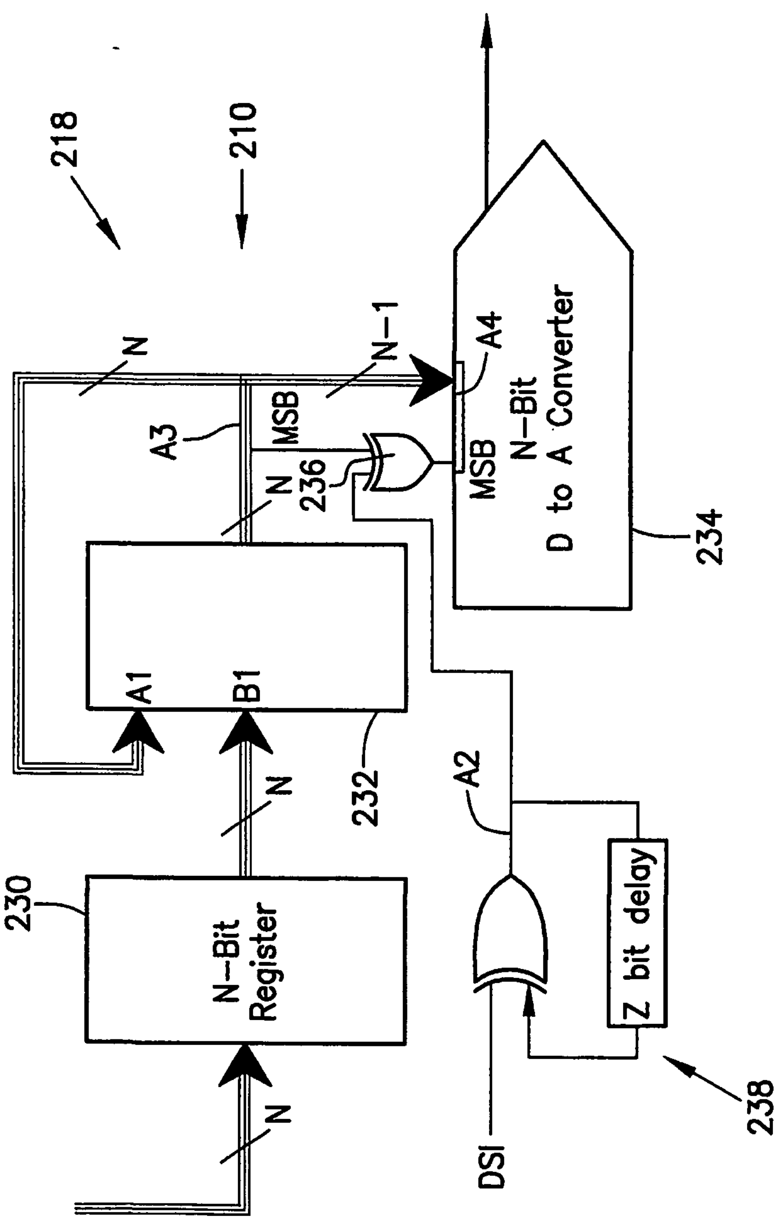

218
210
N
N-1
A4
A3
MSB
236
N
MSB
N-Bit
D to A Converter
234
A1
B1
232
N
230
N-Bit
Register
N
A2
Z bit delay
238
DSI

Fig. 6

← time

DSI	1	0	1	1	0	1	1	1	0	
A2	0	1	1	0	1	1	0	1	0	0
A3	001	000	111	110	101	100	011	010	001	000
A4	001	100	011	110	001	000	011	110	001	000
Phase In Fiber	45	180	135	270	45	0	135	270	45	0
Phase in 1st Arm	60	195	150	285	60	15	150	285	60	15
Phase in 2d Arm	60	15	150	285	240	15	510	285	240	
Output	1	0	1	1	0	1	1	1	0	

Fig. 7

← time

DSI	0	0	0	0	0	0	0	0	0	
A2	0	0	0	0	0	0	0	0	0	0
A3	001	000	111	110	101	100	011	010	001	000
A4	001	000	111	110	101	100	011	010	001	000
Phase In Fiber	45	0	315	270	225	180	135	90	45	0
Phase in 1st Arm	60	15	330	285	240	195	150	105	60	15
Phase in 2d Arm	240	555	510	465	420	375	330	285	240	
Output	0	0	0	0	0	0	0	0	0	

Fig. 8

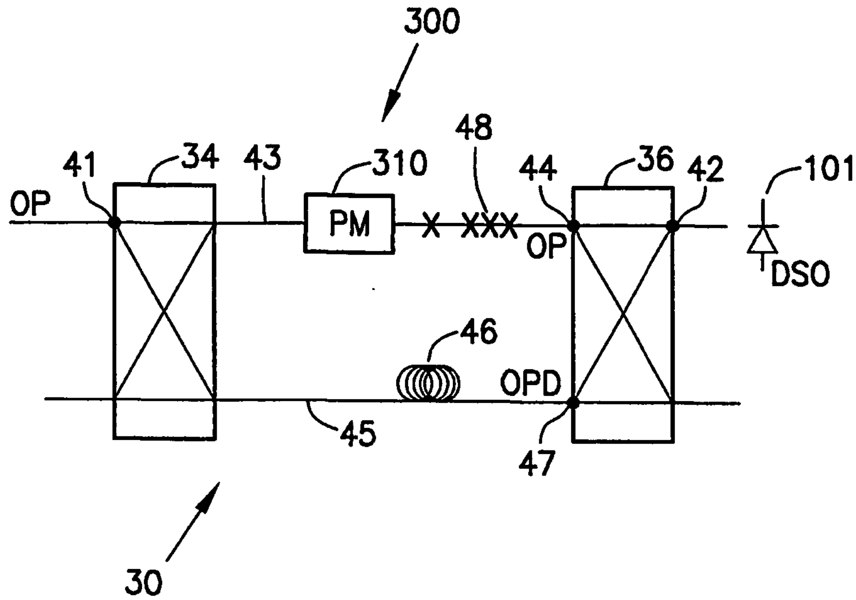

300
48
41
34
43
310
44
36
42
101
OP
PM
OP
DSO
46
OPD
45
47
30

Fig. 9

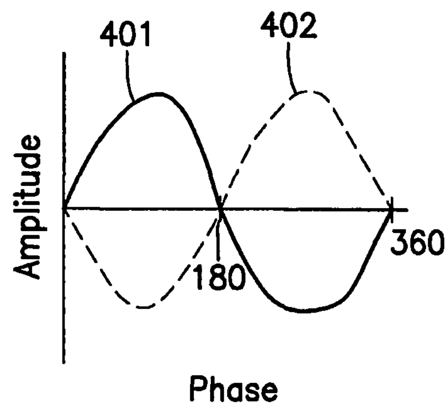

401
402
Amplitude
180
360
Phase

Fig. 10

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US02/07889

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H04B 10/00

US CL : 359/183, 181, 124

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/183, 181, 124

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 5,745,613 A (FUKUCHI et al) 28 April 1998 (28.04.1998), FIG 1, 6, 7	1, 7, 9, 14, 16, 17 ----------- 2, 3, 5, 6, 8, 10, 12, 13, 15, 18, 11, 19
Y	US 6,097,525 A (ONO et al) 01 August 2000 (01.08.2000), col. 2 lines 24-27	2, 3, 8, 15
Y, E	US 6,404,528 B1 (PFEIFFER) 11 June 2002 (11.06.2002), FIG 3	5, 6, 10, 11, 12, 13, 18, 19
Y, P	US 6,215,565 B1 (DAVIS et al) 10 April 2001 (10.04.2001), FIG 1	6, 12, 19
A	US 6,124,960 A (GARTHE et al) 26 September 2000 (26.09.2000), FIG 2	1-19

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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Date of the actual completion of the international search 20 June 2002 (20.06.2002)	Date of mailing of the international search report 08 AUG 2002
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703)305-3230	Authorized officer Jason Chan Telephone No. (703)305-3900